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Towards Real-time Structural Evaluation of In-Service Airfield Pavement Systems Using Neural Networks Approach

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ABSTRACT
The primary objective of this study was to assess the pavement structural deterioration based on Non-Destructive Test (NDT) data using an Artificial Neural Networks (ANN) based approach. ANN-based prediction models were developed for rapid determination of flexible airfield pavement layer stiffnesses from actual NDT deflection data collected in the field in real time. For training the ANN models, ILLI-PAVE, an advanced finite-element pavement structural model which can account for non-linearity in the unbound pavement granular layers and subgrade layers, was employed. Using the ANN-predicted moduli based on the NDT test results, the relative severity effects of simulated Boeing 777 (B777) and Boeing 747 (B747) aircraft gear trafficking on the structural deterioration of National Airport Pavement Test Facility (NAPTF) flexible pavement test sections were characterized.

INTRODUCTION

The National Airport Pavement Test Facility (NAPTF) is located at the Federal Aviation Administration's (FAA) William J. Hughes Technical Center near Atlantic City International Airport, New Jersey, USA. It was constructed to support the development of advanced mechanistic-based airport pavement design procedures especially for New Generation Aircraft (NGA) such as Boeing 777, based on full-scale traffic test data.

The first series of test pavements, referred to as Construction Cycle 1 (CC-1), consisted of nine instrumented test pavements (six flexible and three rigid) that were 18.3 m (60 ft) wide and total 274.3 m (900 ft) in length. The nine test pavements were built on three different subgrade materials: low-strength (target California Bearing Ratio [CBR] of 4), medium-strength (target CBR of 8), and high-strength (target CBR of 20).

During the first series of traffic tests at NAPTF, a simulated six-wheel Boeing 777 (B777) landing gear in one lane and a four-wheel Boeing 747 (B747) landing gear in the other lane were trafficked simultaneously until the test pavements were deemed failed. Non-Destructive Tests (NDT) using both Falling Weight Deflectometer (FWD) and Heavy Weight Deflectometer (HWD) were conducted to document the uniformity of pavement and subgrade construction as well as to monitor the effect of full-scale trafficking on pavement response and performance over time.

Based on the results from the sensitivity studies at the NAPTF and Denver International Airport (DIA), the amplitude of the impulse load does not seem to be critical provided the generated deflections are within the limits of all deflection sensors (McQueen et al., 2001; Lee et al., 1997). In this study, an ANN-based methodology was developed to backcalculate the Asphalt Concrete (AC) and subgrade moduli from the 40-kN (9,000-lb) NDT test data acquired at NAPTF during full-scale dynamic, simulated traffic testing.

ANN BASED STIFFNESS PREDICTION MODELS

The Elastic Layered Programs (ELPs) used in the analysis and design of flexible pavements consider the pavement as an elastic multi-layered media, and assume that pavement materials are linear-elastic, homogeneous and isotropic. However, the unbound granular materials and fine-grained subgrade soils, referred to as pavement geomaterials, do not follow a linear stress-strain behavior under repeated traffic loading. The non-linearity or stress-dependency of resilient modulus for unbound granular materials and cohesive fine-grained subgrade soils has been well established (Garg *et al.* 1998). Unbound aggregates exhibit stress hardening type behavior whereas fine-grained subgrade soils show stress-softening type behavior. Also, previous research studies have shown the non-linearity of underlying pavement layers at the NAPTF (Gomez-Ramirez and Thompson 2002; Garg and Marsey 2002).

Over the years, ANNs have emerged as successful computational tools for studying a majority of pavement engineering problems (Meier and Rix 1995; Ceylan et al. 2005). Recent research studies at the Iowa State University and University of Illinois have focused on the development of ANN based forward and backcalculation type highway flexible pavement analysis models to predict critical pavement responses and layer moduli, respectively (Ceylan et al. 2005). Gopalakrishnan *et al.* (2006) and Gopalakrishnan and Thompson (2004) successfully demonstrated the ANN-based approach for backcalculating airport flexible pavement layer moduli from HWD test data, specifically targeted towards the study of NAPTF flexible pavement sections.

In the current study, ANN models that were originally developed and validated for predicting the pavement layer moduli from the 40-kN (9,000-lb) FWD deflection basins of highway flexible pavements, were used in backcalculating flexible pavement layer moduli from 40-kN (9,000-lb) FWD data acquired during full-scale traffic testing at the NAPTF.

GENERATION OF SYNTHETIC DATABASE

Developed at the University of Illinois (Raad and Figueroa 1980), ILLI-PAVE is an axisymmetric finite element (FE) program commonly used in the structural analysis of flexible pavements. It models the pavement as a two-dimensional axisymmetric solid of revolution and employs nonlinear stress-dependent models and failure criteria for granular materials and fine-grained soils. In this study, the goal was to establish a database of ILLI-PAVE response solutions that would eventually constitute the training and testing data sets for developing ANN-based structural models for the rapid backcalculation analyses.

A generic three-layer flexible pavement structure consisting of AC surface layer, unbound aggregate base layer, and subgrade layer was modeled in ILLI-PAVE. The top surface AC layer was characterized as a linear elastic material with Young's Modulus, E_{AC}, and Poisson ratio, ν. The K-θ model (Hicks and Monismith 1971) was used as the non-linear characterization model for the unbound aggregate layer ($E_R = K\theta^n$; where E_R is the resilient modulus, θ is bulk stress, and K and n are regression parameters and are related through a regression equation).

Fine-grained soils were considered as "no-friction" but cohesion only materials and modeled using the commonly used bi-linear model (Thompson and Elliot 1985) for resilient modulus characterization. As indicated by Thompson and Elliot (1985), the value of the resilient modulus at the breakpoint in the bilinear curve, E_{Ri}, can be used to classify fine-grained soils as being soft, medium or stiff. The E_{Ri} is the main input for subgrade soils in ILLI-PAVE. The bilinear model parameters were set to default values. The 40-kN (9-kip) wheel load was applied as a uniform pressure of 552 kPa (80 psi) over a circular area of radius 152 mm (6 in) simulating the FWD loading.

Backpropagation type artificial neural network models (Haykin 1999) were trained in this study with the ILLI-PAVE synthetic solutions database and were used as rapid analysis tools for predicting flexible pavement layer moduli. Backpropagation type neural networks were used to develop two ANN structural models with different network architectures for predicting the pavement layer moduli (E_{AC} and E_{Ri}) using the FWD deflection data and pavement layer thicknesses.

In this study, the 8-60-60-1 (eight inputs, two hidden layers with 60 hidden neurons each, and one output) architecture was chosen as the best architecture for the ANN models based on its lowest training and testing Mean Square Errors (MSEs) in the order of 1×10^{-4} (corresponding to a Root Mean Squared Error [RMSE] of 0.3%) for both output variables, E_{AC} and E_{Ri}.

Figure 1 depicts the prediction ability of the 8-60-60-1 network at the 10,000th training epoch showing very low Average Absolute Errors (AAEs). The development of ANN backcalculation models employed in this study are discussed in detail by Ceylan et al. (2005).

To fulfill the objectives of this study, the developed ANN models were applied to the field FWD data acquired at the NAPTF during full-scale traffic testing of flexible pavement sections using six-wheel and four-wheel heavy aircraft gear loading. A description of the NAPTF pavement testing program follows.

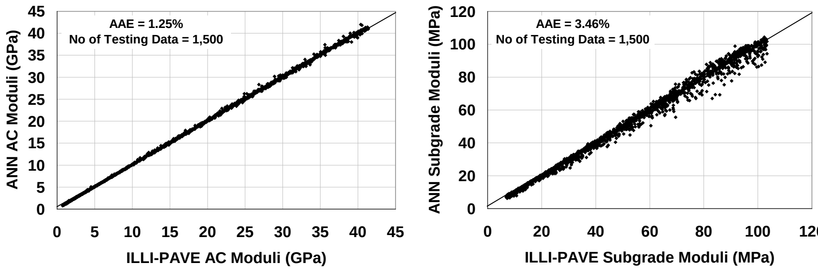

Figure 1. Performance of ANN stiffness prediction models

NATIONAL AIRPORT PAVEMENT TEST FACILITY (NAPTF)

In this study, the following medium-strength subgrade flexible pavement test section was considered: MFC – a conventional granular base flexible pavement. The MFC section had 127-mm of P-401 AC, 200-mm of P-209 granular base (crushed stone), 307-mm of P-154 granular subbase (grey quarry blend fines) over a medium-strength subgrade (CL-CH DuPont Clay as per ASTM Unified Soil Classification System).

During CC-1 traffic testing, a six-wheel dual-tridem (B777) landing gear was loaded on the north wheel track (LANE 2) while the south side (LANE 5) was loaded with a four-wheel dual-tandem (B747) landing gear at a wheel load of 20,412 kg (45,000 lbs) (Hayhoe et al 2003; Gopalakrishnan 2004). The NAPTF test sections were trafficked until they were deemed structurally failed.

NON-DESTRUCTIVE TESTING AT NAPTF

The FWD/HWD equipment measures pavement surface response (i.e., deflections) from an applied dynamic load that simulates a moving wheel (FAA 2004). Many studies have addressed the interpretation of FWD/HWD pavement deflection measurements as a tool to characterize pavement-subgrade systems (Bush and Baladi 1989, Tayabji and Lukanen 2000).

Nondestructive tests using both FWD and HWD were conducted on NAPTF flexible pavement test sections at various times (McQueen et al 2001). In this study, the focus is on 53.4-kN (12,000-lb) HWD test results. The deflections were measured at radial offsets of 0-mm (D_0), 305-mm (D_1), 610-mm (D_2), 914-mm (D_3), 1219-mm (D_4), and 1524-mm (D_5) intervals from the center of the load. The HWD tests were performed on the untrafficked C/L and on the B777 and B747 traffic lanes (LANE 2 and LANE 5).

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NAPTF PAVEMENT STIFFNESS ASSESSMENT USING ANN MODELS

The ANN backcalculation models described in this paper have been developed for backcalculating pavement layer moduli from 40-kN (9,000-lb) FWD deflection basins. Since 40-kN (9,000-lb) FWD tests were not conducted during the course of NAPTF trafficking, the 53.4-kN (12,000-lb) HWD deflection basins were normalized to 40-kN (9,000-lb) loading as the deflections were fairly linear in this range.

The variations in ANN-based backcalculated AC moduli (E_{AC}) with the number of traffic load repetitions (N) are shown in figure 2 for MFC test section. The results are shown for the B777 and B747 traffic lanes as well as the untrafficked Centerline (C/L). Note that the changes in E_{AC} values in the untrafficked C/L were mainly due to the changes in the AC temperature. The temperature of the AC layer at the time of FWD testing has a significant influence on the surface deflections as well as the backcalculated AC modulus.

With increasing traffic load repetitions, the traffic lane E_{AC} values were distinguishably lower than the C/L values indicating loss of stiffness resulting from trafficking. Also, the B747 traffic lane E_{AC} values were consistently lower than those obtained from the B777 traffic lane indicating relative severity effects.

The variations in ANN-based backcalculated non-linear stress-dependent subgrade moduli (E_{Ri}) with increasing number of traffic load repetitions are shown in figure 2 for MFC test section. The E_{Ri} values varied within a range of 60 – 80 MPa during the course of traffic testing. These results are consistent with the laboratory resilient modulus tests (AASHTO T292) conducted on NAPTF subgrade soil samples (Hayhoe and Garg 2001, Gopalakrishnan 2004). In figure 3, the ANN predictions are compared with results from ILLI-PAVE regression algorithms developed by Thompson (1989). The differences in the moduli predictions is attributable to the difference in methodologies (ANN versus regression).

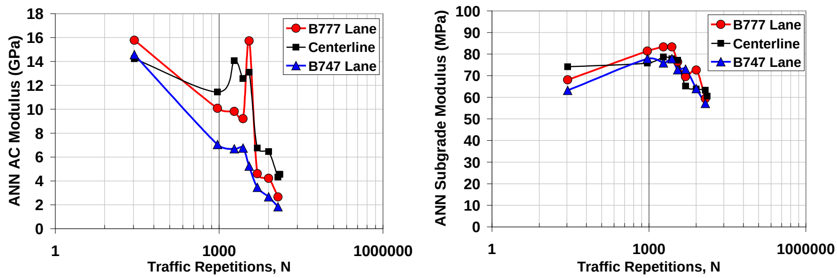

Figure 2. Variations in ANN predicted layer moduli during NAPTF traffic testing

SUMMARY AND CONCLUSIONS

A study was undertaken to backcalculate the AC and subgrade moduli from NDT deflection data acquired at FAA's NAPTF during the full-scale traffic testing using an ANN based approach. Previous studies successfully demonstrated the ANN-based approach for backcalculating airport flexible pavement layer moduli from 160-kN (36,000-lb) HWD test data, specifically targeted towards the study of NAPTF flexible pavement sections. However, limited range of input properties were considered in developing the ANN training database.

In this study, validated ANN models trained over a comprehensive database of 28,500 datasets were employed for pavement layer moduli predictions. The ILLI-PAVE finite element synthetic solutions database, considering the non-linear, stress-dependent unbound granular layer and subgrade soil properties, were used for training the ANN. The ANN models successfully predicted the pavement layer moduli from the ILLI-PAVE finite element solutions. The best-performance ANN models were used to evaluate the NDT data acquired at the NAPTF during full-scale traffic testing with a dual-tandem Boeing 747 (B747) gear and dual-tridem Boeing 777 (B777) gear. The rapid prediction ability of the ANN based pavement stiffness prediction models makes them promising evaluation tools for analyzing NDT deflection data in real-time for both project-specific and network-level FWD testing of airport pavement systems.

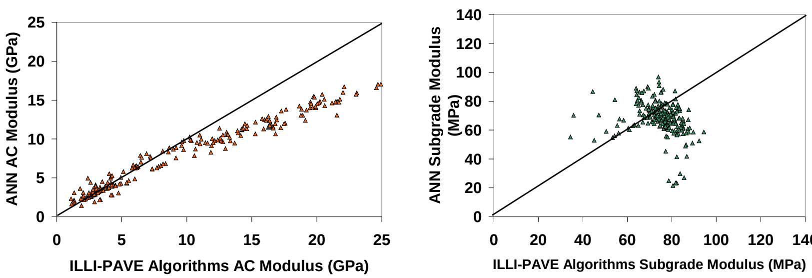

Figure 3. ANN moduli predictions compared with regression algorithm (Thompson, 1989) results

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